Overview of the Neutron Decay Physics

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A brief review of:

- neutron decay parameters, and
- reasons to measure them more precisely.

nBETA collab. mtg.
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BETA DECAY: the basics

In SM $d \to u e^- \bar{\nu}$ (and $u \to d e^+ \nu$) comes from W exchange:

$$H = \frac{G_F}{\sqrt{2}} V_{ud} \bar{e} \gamma_\mu (1-\gamma_5) \nu \bar{u} \gamma^\mu (1-\gamma_5) d + \text{h.c.} \ ,$$

with

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2} \qquad \text{with} \qquad g \sin\theta_W = e$$

Here W couples only to the $\nu_e^{(L)}$ and $\bar{\nu}_e^{(R)}$, giving rise to the $V - A$ form of the interaction.

This determines the main decay properties:

- Weak interaction $\Rightarrow$ long lifetimes ($\tau_n \simeq 15\,\text{min}$).
- Parity violation in GT (A) decays (Lee and Yang).
- Access to information on weak interaction & nucleon structure.

NEUTRON BETA DECAY

$$n \to p + e^- + \bar{\nu}_e + 782\,\mathrm{keV}$$

Due to large mass, the N is nearly static.

N has internal structure $\Rightarrow$ coupl. const. g turns into form factors:

$g_V \quad g_A \quad g_M \quad g_P$	first class
$g_S \quad g_T$	second class

SM gives:

$$g_V = 1 \qquad g_M = \mu_p - \mu_n \qquad g_A \simeq 1.27$$

$$g_P = 0 \qquad g_S = 0 \qquad g_T = 0$$

(renormalizability)

Neutron decay cont'd.

Effective currents:

$$V_\mu = i\bar{\psi}_p\left[g_V(k^2)\gamma_\mu + \frac{g_M(k^2)}{2m_p}\sigma_{\mu\nu}k^\nu + ig_S(k^2)k_\mu\right]\psi_n$$

$$A_\mu = i\bar{\psi}_p\left[g_A(k^2)\gamma_\mu\gamma_5 + \frac{g_T(k^2)}{2m_p}\sigma_{\mu\nu}k^\nu\gamma_5 + ig_P(k^2)k_\mu\gamma_5\right]\psi_n$$

where k_μ is the mom. transfer from N to the $e\bar{\nu}$.

Due to small momentum transfer, we have the weak charged coupling constants

$$G_V = V_{ud}\, g_V(k^2 \to 0)G_F \qquad \text{and} \qquad G_A = V_{ud}\, g_A(k^2 \to 0)G_F \ ,$$

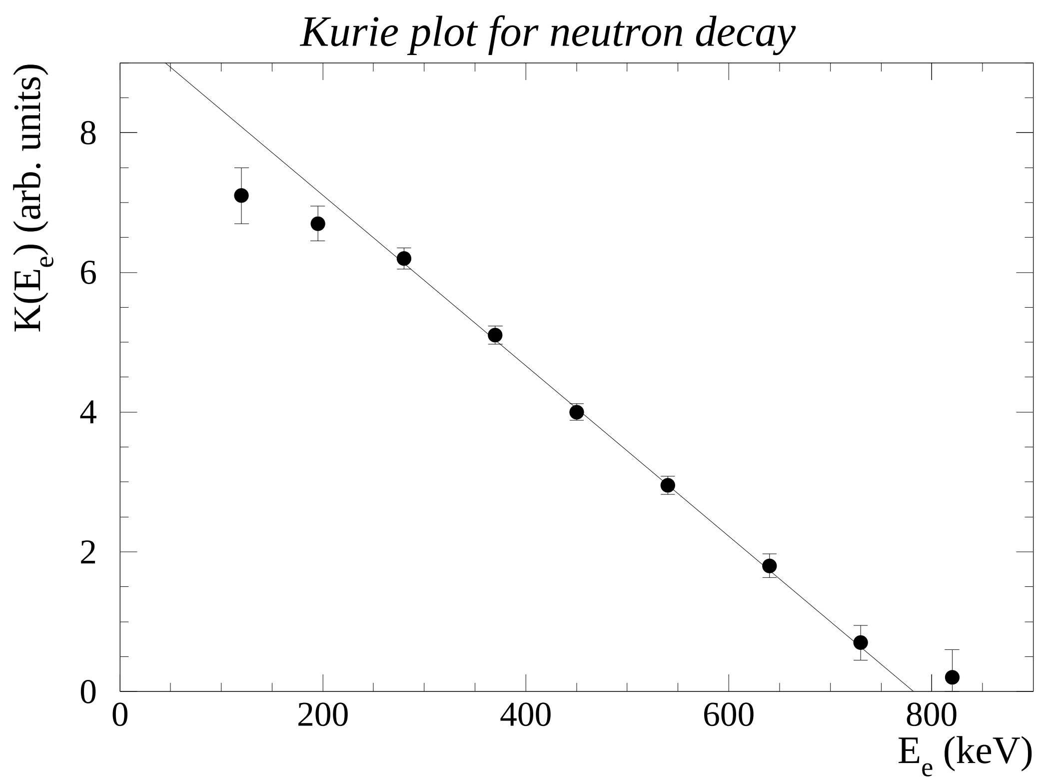
so that

$$\boxed{\lambda \equiv \frac{G_A}{G_V} \equiv \frac{g_A}{g_V}} \ .$$

n DECAY OBSERVABLES: 1. Electron energy spectrum

$$\frac{dw}{dE_e} \propto |\vec{k}_e| E_e \left(E_0 - E_e\right)^2 \quad \text{so that} \quad K(E_e) = \left(\frac{1}{|\vec{k}_e| E_e} \frac{dw}{dE_e}\right)^{1/2}$$

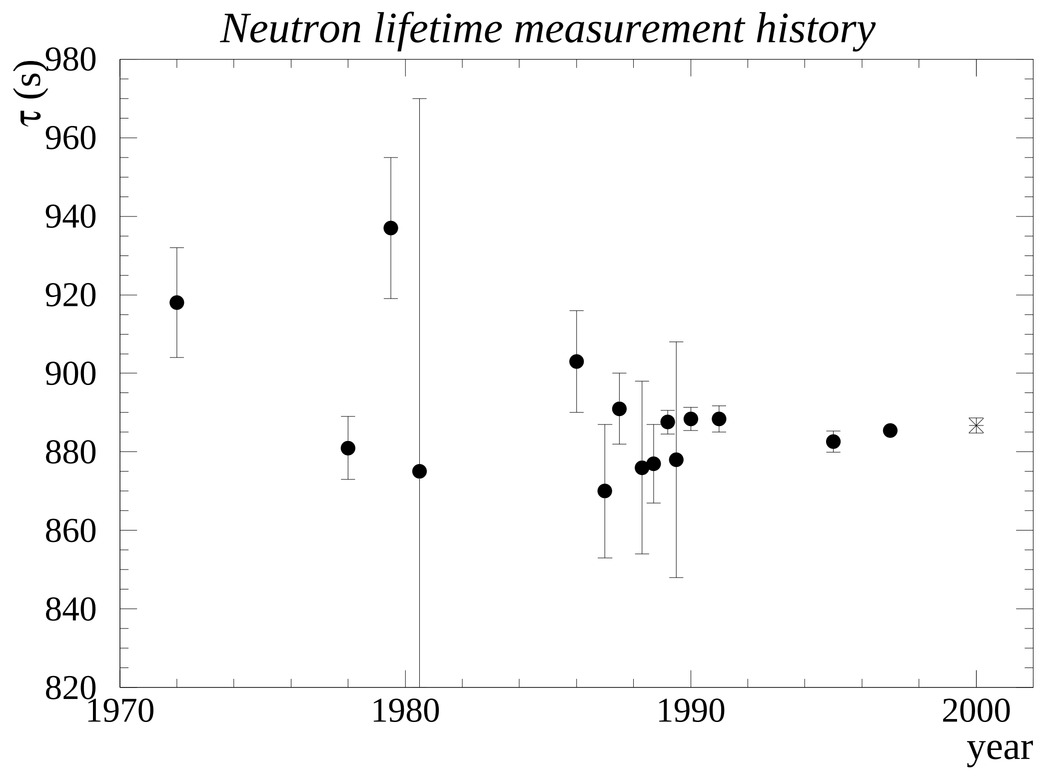
produces the familiar linear (Fermi-)Kurie plot:



n DECAY OBSERVABLES: 2. Neutron lifetime

$$\tau = \frac{2\pi^3\hbar^7}{f^R m_e^5 c^4} \frac{1}{G_V^2 + 3G_A^2} \propto \frac{1}{G_V^2(1+3\lambda^2)}$$

$\lambda = \dfrac{g_A}{g_V}$; phase space factor $f^R = 1.71482(15)$



n Decay Observables: 3. Angular correlations

In the SM:

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \simeq k_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + a \frac{\vec{k}_e \cdot \vec{k}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A \frac{\vec{k}_e}{E_e} + B \frac{\vec{k}_\nu}{E_\nu} + D \frac{\vec{k}_e \times \vec{k}_\nu}{E_e E_\nu} \right) \right]$$

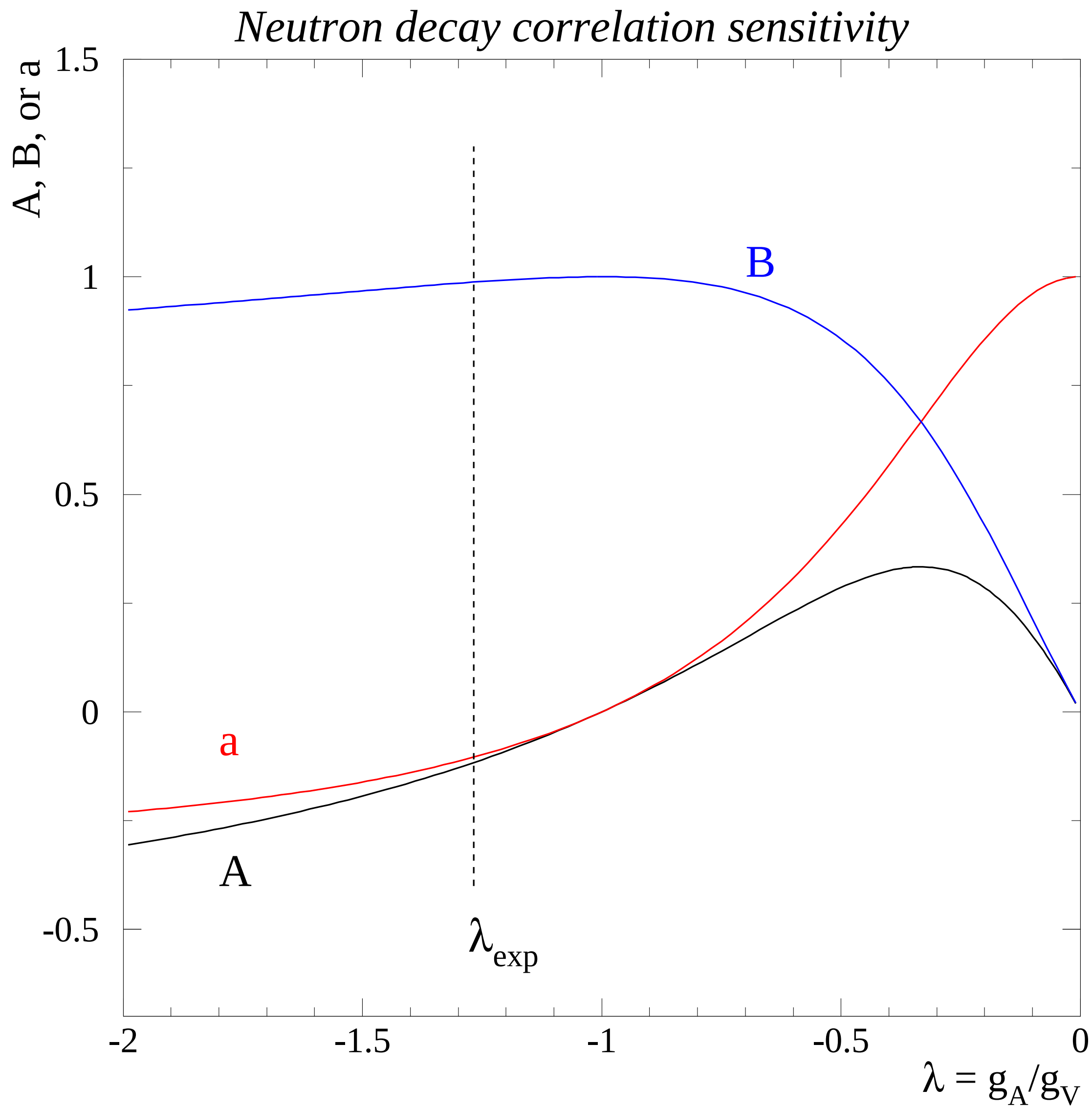
with:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2 \frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

$$B = 2 \frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad D = 2 \frac{Im(\lambda)}{1 + 3|\lambda|^2}$$

$\lambda = \dfrac{g_A}{g_V}$ ($D \neq 0 \Leftrightarrow T$ invariance violation.)

Sensitivity to λ:



THE BIG A

Due to weak magnetism corrections, g_A–g_V interference, N recoil, one measures:

$$w(\theta) = 1 + \frac{v}{c} P_n A \cos\theta \ ,$$

where $\theta = \angle(\vec{k}_e, \vec{\sigma}_n)$, with

$$A = A_0 \left[1 + A_{\mu m} \left(A_1 W_0 + A_2 W + A_3 W\right)\right]$$

where

$$W = \frac{E_e}{mc^2} + 1 \qquad W_0 = \frac{E_0}{mc^2} + 1$$

A_i's, plus a radiative correction of $\mathcal{O}(10^{-3})$ well controlled.

It is A_0 that we are after:

$$A_0 = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

CURRENT VALUES OF n PARAMETERS

param.	PDG 2002 value	$\not P$	$\not T$	PERKEO II May '02:
a	-0.102 ± 0.005	N	N	
A	-0.1162 ± 0.0013	Y	N	-0.1189 ± 0.0007 !!
B	0.983 ± 0.004	Y	N	
D	$(-0.6 \pm 1.0) \times 10^{-3}$	N	Y	
b	never measured			
ϕ_{AV}	$(180.08 \pm 0.10)^\circ$			
g_a/g_V	-1.2670 ± 0.0030			-1.2739 ± 0.0019 !!
τ_n	$885.7 \pm 0.8\,\mathrm{s}$			

CONSISTENCY CHECKS ON NEW PHYSICS

- Unitarity of the CKM matrix (τ_n, λ)
  - coupling to 4^{th} q generation
    - mass scale of compositeness, Λ
    - mass of additional Z' bosons
    - aspects of certain SUSY SM extensions
    - signal of a smaller G_F? (ν oscillations)

- Non-SM terms in the $\mathcal{L}$ (S, P, T)
  - LR symmetric models
    - exotic fermions
    - leptoquarks
    - composite models

- T-violation through D, R (non-KM $\cancel{\mathrm{CP}}$)

  [T-even FS contribution $\sim 1/10$ of that for ^{19}Ne]

STATUS OF CKM UNITARITY

- $|V_{us}| \simeq 0.2196 \pm 0.0026$ from K_{e3} decays.
- $|V_{ub}| \simeq 0.0036 \pm 0.0007$ from B decays.
- $|V_{ud}|$ from superallowed Fermi nuclear β decays

  1990 Hardy reconciled Ormand & Brown's and Towner's ft values:

  $$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9962 \pm 0.0016, \qquad \text{or } 1 - 2.4\sigma.$$

- $|V_{ud}|$ from neutron β decay

  $$\sum |V_{ui}|^2 = 0.9917(28), \text{ or } 1 - 3.0\sigma. \qquad [\text{PERKEO II (2002)}]$$

- $|V_{ud}|$ from pion β decay
  $BR \simeq 10^{-8}$; PIBETA expt; presently $\lesssim 1\%$ precision,
  $\sim 0.5 - 0.6\%$ expected soon.

MANIFESTLY LR SYMMETRIC MODELS

- In the SM, weak interactions obey the $SU(2)_L \times U(1)$ symmetry group, with maximal P violation and only $\nu^{(L)}$ and $\bar{\nu}^{(R)}$.
- Early universe was 100% LR symmetric.
- $\nu^{(R)}$ are thus relics of the early universe.

The simplest $SU(2)_R \times SU(2)_L \times U(1)$ scheme keeps

$$g_L = g_R \quad \text{and} \quad V_{ij}^L = V_{ij}^R$$

and requires new W_R, Z' which mix:

$$\begin{aligned} W_L &= W_1 \cos\zeta + W_2 \sin\zeta \\ W_R &= e^{i\omega}(-W_1 \sin\zeta + W_2 \cos\zeta) \end{aligned}$$

with

$$m(W_1) = m_1 \quad \text{and} \quad m(W_2) = m_2$$

LR Symmetric models (2)

$\mathcal{L}_{\text{eff}}$ of beta decay gets new quantities [Holstein + Treiman, '77]:

$$r_V = \frac{1+\eta_{VA}}{1-\eta_{VA}}, \qquad r_A = \frac{\eta_{AA}+\eta_{VA}}{\eta_{AA}-\eta_{VA}},$$

with

$$\eta_{AA} = \frac{\epsilon^2+\delta}{\epsilon^2\delta+1}, \quad \eta_{VA} = -\epsilon\frac{1+\delta}{\epsilon^2\delta+1},$$

where

$$\delta = \frac{m_1}{m_2}, \quad \epsilon = \frac{1+\tan\zeta}{1-\tan\zeta}.$$

Now the rates of beta decays become:

$$\begin{aligned} G_V^2 \quad &\Rightarrow \quad G_V^2(1+r_V^2) \\ G_V^2+3G_A^2 \quad &\Rightarrow \quad G_V^2(1+r_V^2)+3G_A^2(1+r_A^2) \end{aligned}$$

LR symmetric models (3)

Neutron decay correlation coefficients become:

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \quad \Rightarrow \quad \frac{(1+r_V^2)-\lambda^2(1+r_A^2)}{(1+r_V^2)+3\lambda^2(1+r_A^2)}$$

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \quad \Rightarrow \quad -2\frac{\lambda(\lambda+1)(1+r_V^2)-r_A\lambda(r_A\lambda+r_V)}{(1+r_V^2)+3\lambda^2(1+r_A^2)}$$

$$B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2} \quad \Rightarrow \quad 2\frac{\lambda(\lambda-1)(1+r_V^2)-r_A\lambda(r_A\lambda-r_V)}{(1+r_V^2)+3\lambda^2(1+r_A^2)}$$

In other words, measuring A, a, and B determines λ, ζ, and $\dfrac{m_1}{m_2}$.

THE FIERZ INTERFERENCE TERM b

b can be estimated from nuclear beta decays:

$$b_F = \frac{C_S C_V}{|C_S|^2 + |C_V|^2} \qquad b_{GT} = \frac{C_T C_A}{|C_T|^2 + |C_A|^2}$$

These terms vanish for pure $\nu^{(R)}$ coupling.

$b \neq 0$ only for S, T coupling to $\nu^{(L)}$. (leptoquarks?)

From $0^+ \to 0^+$ decays [Towner + Hardy '98]:

$$|b_F| \simeq \frac{|C_S|}{|C_V|} \leq 0.0077 \ (90\,\% \text{ c.l.})$$

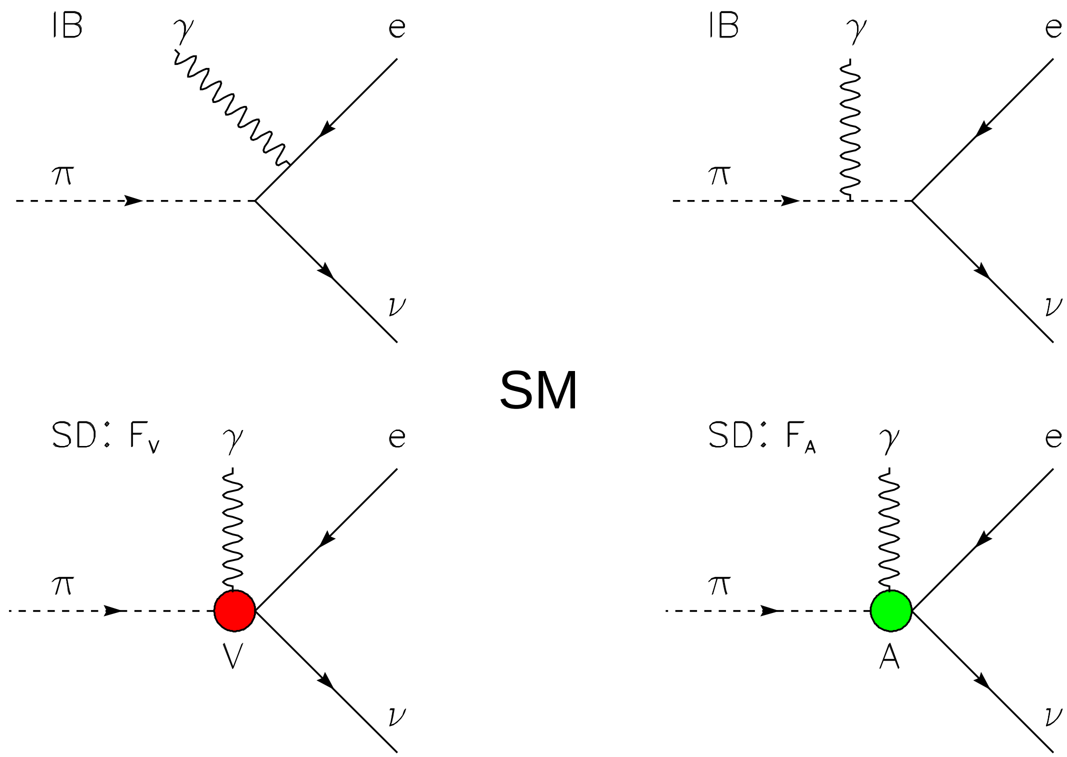
From analysis of GT decays [Deutsch + Quin, '95]:

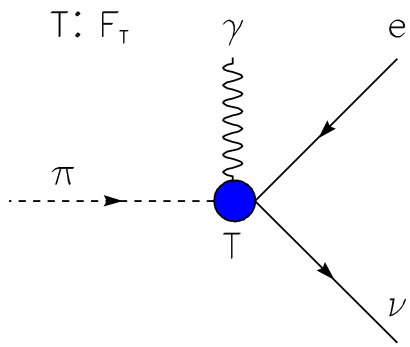
$$b_{GT} = -0.0056(51) \simeq \frac{C_T}{|C_A|} \ .$$

$\Rightarrow$ a $\sim 10^{-3}$ measurement of b_n would be very interesting!

Radiative Pion Decay:

$\pi^+ \to e^+ \nu \gamma$

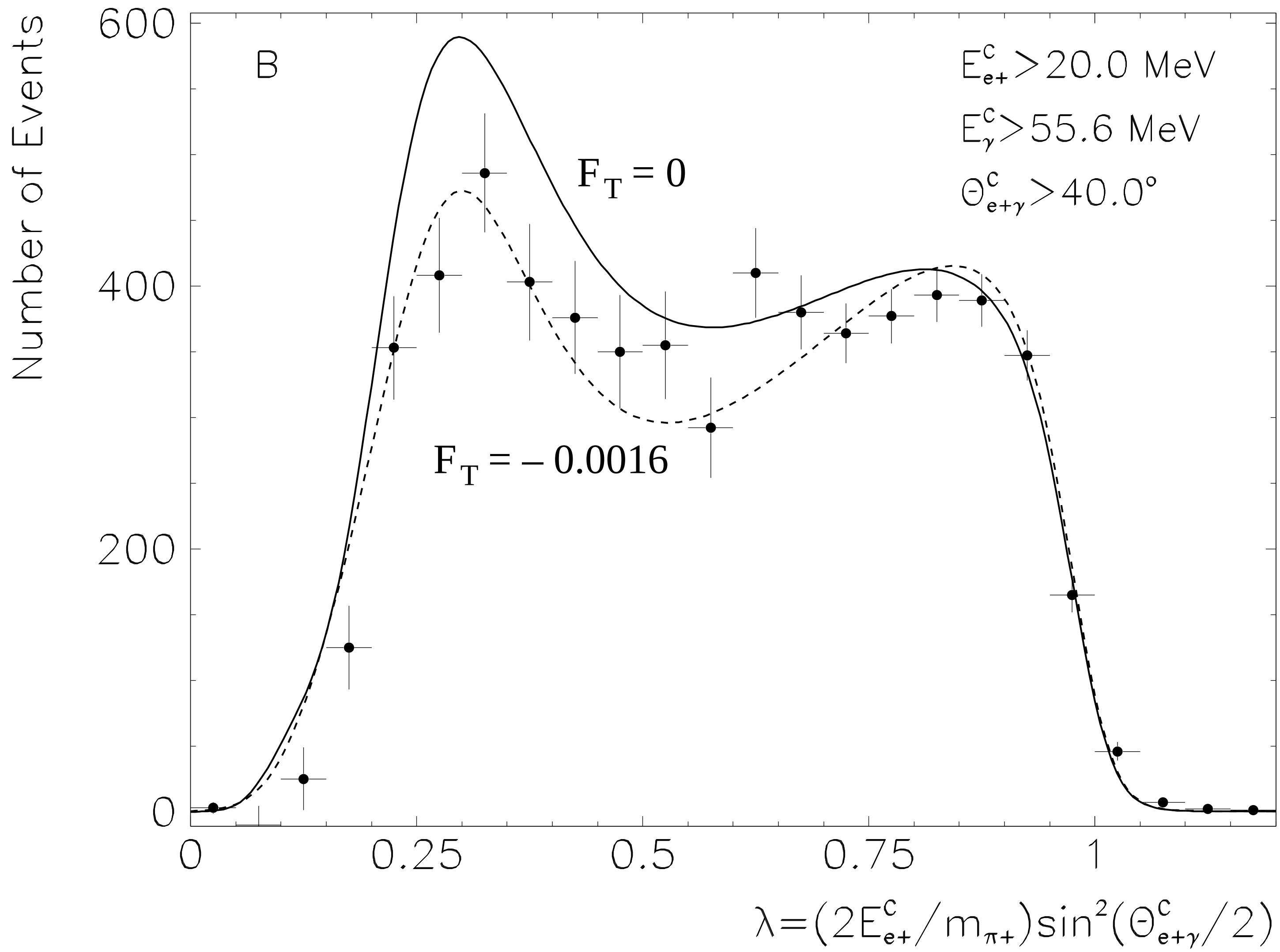




Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

PIBETA expt. PRELIMINARY: $\pi^+ \to e^+\nu\gamma$



PIBETA Pion Form Factors *WORK IN PROGRESS*

Fit	Fixed parameters	Fit parameters	χ^2/df
‘SM’	F_V: 0.0259(5), F_T: 0	F_A: 0.0125(3)	~3
CVC	F_V: 0.0259(5)	F_T: −0.0011(2)	~1.5
+T	F_A: 0.0122(7) (from reg. A)		
CVC	F_V: 0.0259(5)	F_A: 0.0138(4)	~1.2
+T		F_T: −0.0016(3)	

1. We are seeing $F_A/F_V \simeq 0.5$, as expected.
2. Hard γ/soft e^+ events are not well described by standard theory, requiring “$F_T \neq 0$” and a new theoretical look.
3. We can rule out a large $F_T \sim 0.0056$, as reported in analyses of the ISTRA data.

CONCLUSIONS

- A solid case can be made for new, more accurate measurements of the neutron decay parameters: τ_n, a, A, B, b, D.
- Verifiable lack of consistency among these parameters would point to new physics, or to problems in existing SM calculations.
- Current experiments are at the level of interesting precision, and, moreover, are not consistent at the moment.
- More theoretical work may be required to improve precision of calculations due to known SM processes (radiative, loop diagrams).

[Not discussed here: R angular correlation and n radiative decay, interesting and challenging measurements.]